REMARKS

Reconsideration of this application, as amended, is respectfully requested.

THE CLAIMS

Claim 1 has been amended to more positively recite cast steel legs and separately cast, cast steel leg sections, rather than indirectly reciting that each of the leg sections is formed from cast steel as formerly recited in claim 1.

In addition, claim 1 has been amended to incorporate the subject matter of claims 2 and 3, and claim 5 has been amended to be rewritten in independent form along the lines of amended independent claim 1 (but without including the subject matter of claims 2 and 3).

Still further, claims 4 and 13 have been amended to depend from claim 1, claims 8 and 9 have been amended to depend from claim 5, and claim 12 has been amended to better accord with amended independent claim 1.

No new matter has been added and no new issues with respect to patentability have been raised.

Accordingly, it is respectfully requested that the amendments to the claims be approved and entered under 37 CFR 1.116.

THE PRIOR ART REJECTION

Claims 1-17 were all again rejected under 35 USC 102 and/or 35 USC 103 as being anticipated by or rendered obvious in view of one or more of JP 9-209402 ("Kawamura et al"), USP 3,920,081 ("Terai et al"), and USP 6,637,111 ("Sasaki et al"). These rejections, however, are respectfully traversed.

The Examiner contends in item 4 at the bottom of page 4 of the Office Action that the welded plates of steel of the references were at one time cast and therefore disclose the subject matter of the claimed present invention. Indeed, rolled sheets of steel were at one time cast ingots or were formed from continuous castings; see for example, Figure 13.1 on page 348 of the attached reference material[1].

It is respectfully pointed out, however, that after being rolled out from ingots, sheet steel has substantially different mechanical properties from the cast ingots from which it was rolled; see for example, pages 354, 355, 357, and 436 of the attached reference material and specifically Figure 13.6 on page 355 and Table 16.2 on page 436. In addition, it is respectfully pointed out that welding also significantly affects the steel microstructure and therefore the performance of a part

[1] Kalpakjian, Serope; Schmid, Steven R. Manufacturing Engineering and Technology. 5th Ed. Pearson Education, New Jersey: 2006.

as a whole; see, for example, pages 960-969 of the attached reference material.

According to the present invention as recited in amended independent claims 1 and 5, a crawler frame for a construction machine is provided which comprises cast steel legs which are bifurcated into front and rear separately cast, cast steel leg sections. With this structure, complicated welds can be avoided, and the number of parts and welded places of the crawler frame can be reduced, thereby reducing the number of processes required to form the crawler frame. And it is respectfully submitted that the cast steel legs are a structural feature having specific mechanical properties, and that none of the cited references disclose, teach or suggest this feature of the claimed present invention.

On page 2 of the Office Action, the Examiner asserts that Figs. 4 and 6 of Kawamura et al show legs that are bifurcated into front and rear leg sections that are formed of cast steel.

It is respectfully pointed out, however, that an English language translation of Kawamura et al has already been submitted to show that Kawamura et al clearly does not disclose, teach or suggest cast steel legs which are bifurcated into separately cast, cast steel front and rear leg sections. In particular, it is respectfully pointed out that Figs. 16 and 17 of Kawamura et

al show the assembled parts of Figs. 4 and 6 being manufactured from plates of steel.

As explained in paragraph [0018] of the English language translation of Kawamura et al, Fig. 4 shows a track frame 1 made from an upper plate 1U and a lower plate 1D which are bent to have a trapezoidal shape in a front view and are welded respectively to the upper and inner faces of the crawler frames 2. And as shown in Figs. 4 and 17, the upper plate 1U is divided into two parts, namely a left part 1UL and a right part 1UR, which are cut out of a steel sheet SP as shown in Fig. 17. According to Kawamura et al, moreover, the lower plate 1D is a one-piece plate that is cut out from a steel sheet. See paragraphs [0023], [0027] and [0028], for example, of the English language translation of Kawamura et al.

As explained in paragraph [0022] of Kawamura et al, moreover, Fig. 6 shows upper and lower plates 1'U and 1'D which are bent to have a trapezoidal shape in a front view and bridge between the crawler frames 2. And as explained in paragraph [0024], for example, the upper plate 1'U is a one-piece plate that is cut out from a steel sheet SP.

Accordingly, it is respectfully submitted that Kawamura et al is clearly directed to legs of a track frame that are formed from a plurality of pieces that are cut out from steel sheets. And it is respectfully submitted that one of ordinary skill in

the art would have understood the disclosure of a plates of metal in Kawamura et al to mean rolled plates, not cast plates.

It is respectfully submitted that the rolled and welded steel sheets of Kawamura et al do not correspond to the cast steel legs and cast steel leg sections of the claimed present invention as recited in each of amended independent claims 1 and 5.

In addition, it is respectfully submitted that Kawamura et al clearly does not disclose, teach or suggest the features of the present invention as recited in amended independent claim 1 whereby a base section of each leg has a two-part structure, a base section of the front leg section of each leg is securely welded to a base section of the rear leg section of the leg, and the base section of each leg is securely welded to the central frame section.

Indeed, although the Examiner asserts that each of the legs of Kawamura et al has a two part structure, and that the front leg section of each leg is securely welded to the rear section of each leg, it is respectfully pointed out that Kawamura et al in fact discloses forming all of the legs together from a single lower plate, one upper left plate, and one upper right plate, as explained hereinabove. As can be clearly seen in Fig. 17 of Kawamura et al, for example, there is no division of the legs thereof into front and rear portions. Rather, the upper front

and rear portions of each leg are provided integrally in a single part cut out from a steel sheet, and the lower front and rear portions of all of the legs are provided integrally in single plate cut out from a steel sheet.

It is respectfully submitted, therefore, that Kawamura et al clearly does not disclose, teach or suggest welding a base section of a front leg section of a leg to a base section of a rear leg section of the leg. By contrast, according to Kawamura et al the front and rear portions of each leg are integrally formed by being cut out from a same sheet.

Still further, it is respectfully pointed out that according to the present invention as recited in amended independent claim 5, each of the front and rear leg sections of each leg comprises a vertical wall which is formed from cast steel and which is integral with a base section of the respective one of the front and rear leg sections. As pointed out hereinabove, Kawamura et al discloses forming legs from a plurality of plates, and Kawamura et al does not disclose, teach or suggest a vertical wall formed integrally with any of the sections of the legs.

In view of the foregoing, it is respectfully submitted that the present invention as recited in amended independent claims 1 and 5, and dependent claims 4, 6-13, 15 and 17, clearly patentably distinguishes over Kawamura et al, taken singly or

combination with Terai et al and/or Sasaki et al, under 35 USC 102 and 35 USC 103.

Accordingly, entry of this Amendment, allowance of the claims and the passing of this application to issue are respectfully solicited.

If the Examiner has any comments, questions, objections or recommendations, the Examiner is invited to telephone the undersigned at the telephone number given below for prompt action.

Respectfully submitted,

/Douglas Holtz/

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important consideration, since it is used for automotive engine blocks and cylinder heads). New casting techniques are being developed to further improve the machinability of CGI.

Cast steels. Because of the high temperatures required to melt cast steels (up to about 1650°C, 3000°F), casting them requires considerable experience. The high temperatures involved present difficulties in the selection of mold materials, particularly in view of the high reactivity of steels with oxygen during the melting and pouring of the metal. Steel castings possess properties that are more uniform (isotropic) than those made by mechanical working processes (Part III). Cast steels can be welded; however, welding alters the cast microstructure in the heat-affected zone (see Fig. 30.17), thus influencing the strength, ductility, and toughness of the base metal. Subsequent heat treatment must be performed to restore the mechanical properties of the casting. Cast weldments have gained importance for assembling large machines and structures where complex configurations or the size of the casting may prevent casting of the part economically in one location. Cast steels have important applications in equipment for railroads, mining, chemical plants, oil fields, and heavy construction.

Cast stainless steels. Casting of stainless steels involves considerations similar to those for steels. Stainless steels generally have long freezing ranges and high melting temperatures. They can develop several structures, depending on their composition and processing parameters. Cast stainless steels are available in various compositions, and they can be heat treated and welded. These products have high heat and corrosion resistance, especially in the chemical and food industries. Nickel-based casting alloys are used for severely corrosive environments and for very high-temperature service.

12.4 Economics of Casting

As is the case with all manufacturing processes, the cost of each cast part (**unit cost**) depends on several factors, including materials, equipment, and labor. Upon reviewing the various casting processes in Chapter 11, it is noted that some require more labor than others, some require expensive dies and machinery, and some require a great deal of time to produce the castings (Table 12.6). Each of these individual factors

TABLE 12.6

General Cost Characteristics of Casting Processes

Casting process	Cost*			Production rate (pieces/hr)
	Die	Equipment	Labor	
Sand	L	L	L–M	<20
Shell mold	L–M	M–H	L–M	<50
Plaster	L–M	M	M–H	<10
Investment	M–H	L–M	H	<1000
Permanent mold	M	M	L–M	<60
Die	H	H	L–M	<200
Centrifugal	M	H	L–M	<50

*L = low; M = medium; H = high.

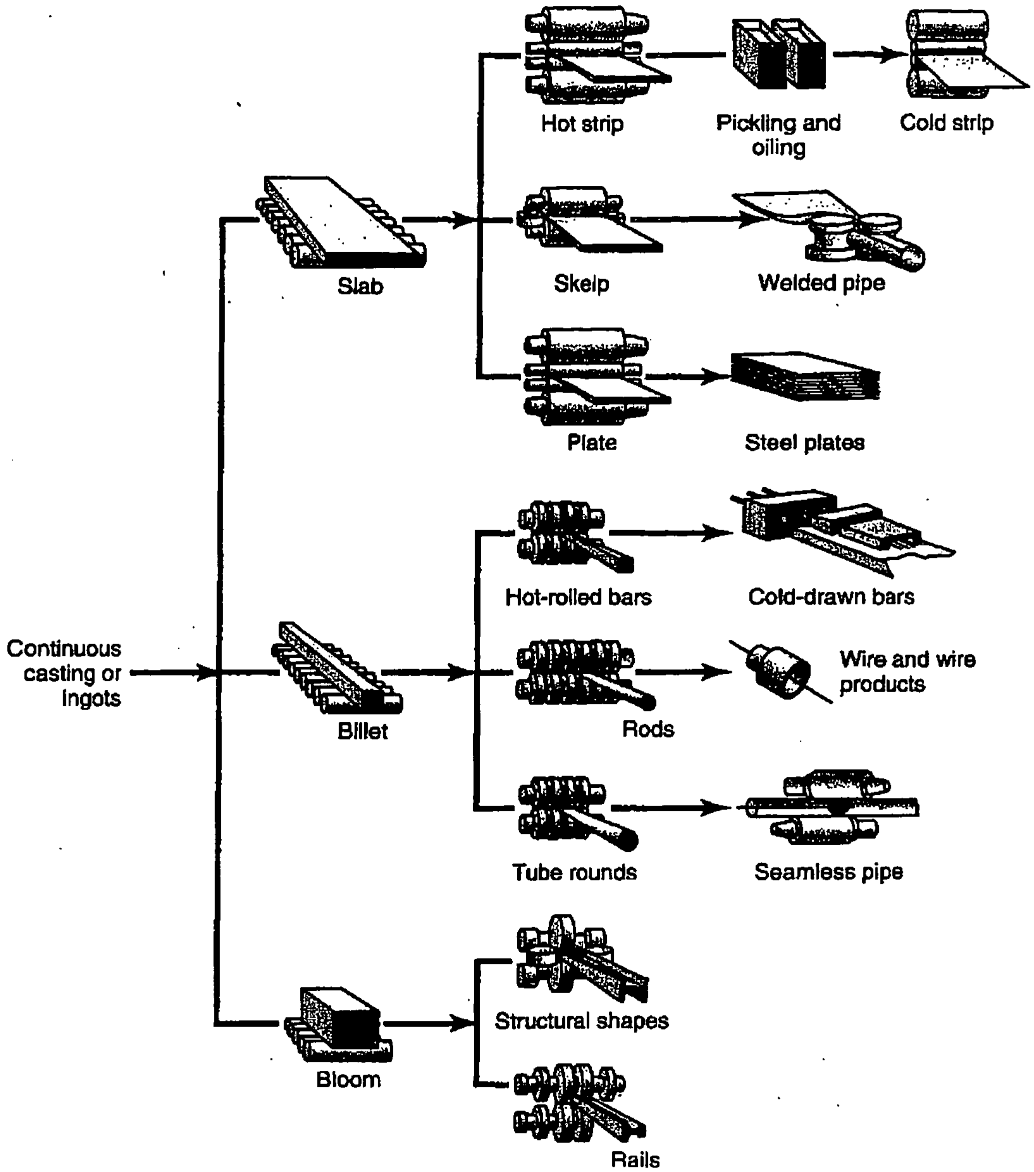

FIGURE 13.1 Schematic outline of various flat-rolling and shape-rolling processes. *Source:* After American Iron and Steel Institute.

and enhanced properties, such as strength and hardness. Subsequently, rolling typically is carried out at room temperature (cold rolling), whereby the rolled product has higher strength and hardness and better surface finish. However, it requires more energy (because of the higher strength of the material at room temperature) and will result in a product with anisotropic properties (due to preferred orientation or mechanical fibering, see Section 1.5).

Plates generally have a thickness of more than 6 mm (1/4 in.) and are used for structural applications, such as ship hulls, boilers, bridges, machinery, and nuclear

vessels. Plates can be as much as 300 mm (12 in.) thick for large structural supports, 150 mm (6 in.) thick for reactor vessels, and 100 to 125 mm (4 to 5 in.) thick for warships and tanks.

Sheets generally are less than 6 mm thick and typically are provided to manufacturing facilities as coils—weighing as much as 30,000 kg (33 tons)—or as flat sheets for further processing into various products. Sheets typically are used for automobile and aircraft bodies, appliances, food and beverage containers, and kitchen and office equipment. Commercial aircraft fuselages and trailer bodies usually are made of a minimum of 1 mm (0.04 in.) thick aluminum-alloy sheets. For example, the skin thickness of a Boeing 747 fuselage is 1.8 mm (0.07 in.) and of a Lockheed L1011 is 1.9 mm (0.075 in.). Steel sheets used for automobile and appliance bodies are typically about 0.7 mm (0.03 in.) thick. Aluminum beverage cans are made from sheets 0.28 mm (0.01 in.) thick. After processing into a can, this sheet metal becomes a cylindrical body with a wall thickness of 0.1 mm (0.004 in.). Aluminum foil (typically used for wrapping and for candy and chewing gum) has a thickness of 0.008 mm (0.0003 in.), although thinner foils down to 0.003 mm (0.0001 in.) also can be produced with a variety of metals.

This chapter describes the fundamentals of flat-rolling and various shape-rolling operations, the production of seamless tubing and pipe, and discusses the important factors involved in rolling practices.

13.2 | The Flat-Rolling Process

A schematic illustration of the *flat-rolling* process is shown in Fig. 13.2a. A metal strip of thickness h_0 enters the **roll gap** and is reduced to thickness h_f by a pair of rotating rolls—each roll being powered individually by electric motors. The surface speed of the rolls is V_r. The velocity of the strip increases from its entry value of V_o as it moves through the roll gap in the same manner in which an incompressible fluid must flow faster as it moves through a converging channel. The velocity of the strip is highest at the exit from the roll gap and is denoted as V_f.

Because the surface speed of the rigid roll is constant, there is *relative sliding* between the roll and the strip along the arc of contact in the roll gap, L. At one point

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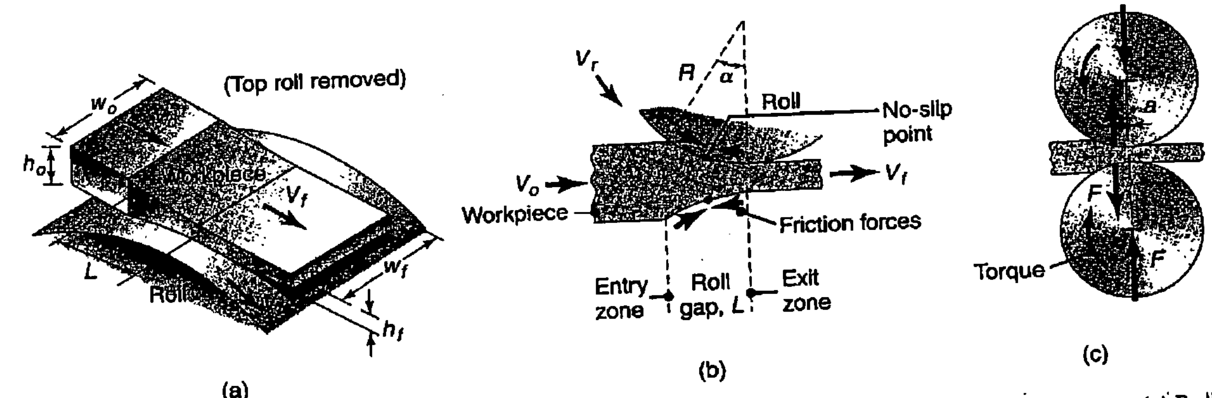

FIGURE 13.2 (a) Schematic illustration of the flat-rolling process. (b) Friction forces acting on strip surfaces. (c) Roll force, F, and the torque, T, acting on the rolls. The width of the strip, w, usually increases during rolling, as shown later in Fig. 13.5.

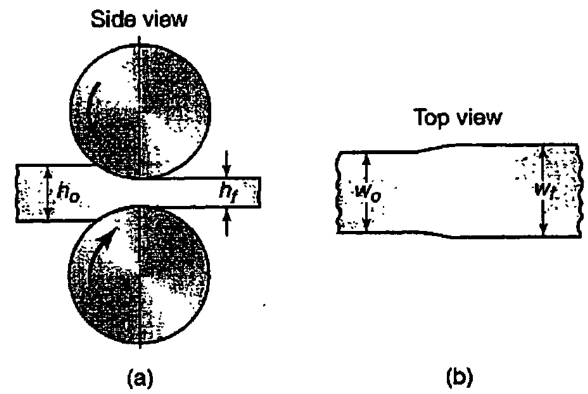

FIGURE 13.5 Increase in strip width (spreading) in flat rolling. Note that similar spreading can be observed when dough is rolled with a rolling pin.

friction, and (c) decreasing ratio of the roll radius to the strip thickness. The last two effects are due to the increased longitudinal constraint of the material flow in the roll gap. Spreading can be prevented also by using additional rolls (with vertical axes) in contact with the edges of the rolled product in the roll gap (*edger mills*), thus providing a physical constraint to spreading.

13.2.3 Vibration and chatter

Vibration and *chatter* can have significant effects on product quality and the productivity of metalworking operations. Chatter, generally defined as *self-excited vibration*, can occur in rolling as well as in extrusion, drawing, machining, and grinding operations. In rolling, it leads to periodic variations in the thickness of the rolled sheet and in its surface finish and, consequently, can lead to excessive scrap (see Table 40.6). Chatter in rolling has been found to occur predominantly in *tandem mills*. Chatter is very detrimental to productivity; it has been estimated, for example, that modern rolling mills could operate at up to 50% higher speeds were it not for chatter.

Chatter is a very complex phenomenon (see also Section 25.4) and results from interactions between the structural dynamics of the mill stand and the dynamics of the rolling operation. Rolling speed and lubrication are found to be the two most important parameters. Although not always practical to implement, it also has been suggested that chatter can be reduced by increasing the distance between the stands of the rolling mill (see Fig. 13.11), increasing the strip width, decreasing the reduction-per-pass (draft), increasing the roll radius, increasing the strip-roll friction, and incorporating dampers in the roll supports.

13.3 Flat-Rolling Practice

The initial rolling steps (*breaking down*) of the material typically is done by hot rolling (above the recrystallization temperature of the metal, Section 1.6). As described in Section 10.2 and illustrated in Fig. 10.2, a cast structure typically is dendritic, and it

includes coarse and nonuniform grains; this structure usually is brittle and may be porous. Hot rolling converts the cast structure to a **wrought structure** (Fig. 13.6) with finer grains and enhanced ductility, both of which result from the breaking up of brittle grain boundaries and the closing up of internal defects (especially porosity). Typical temperature ranges for hot rolling are about 450°C (850°F) for aluminum alloys, up to 1250°C (2300°F) for alloy steels, and up to 1650°C (3000°F) for refractory alloys (see also Table 14.3).

The product of the first hot-rolling operation is called a **bloom** or **slab** (see Fig. 13.1). A bloom usually has a square cross-section, at least 150 mm (6 in.) on the side; a slab usually is rectangular in cross-section. Blooms are processed further by *shape rolling* into structural shapes, such as I-beams and railroad rails (Section 13.5). Slabs are rolled into plates and sheets. **Billets** usually are square (with a cross-sectional area smaller than blooms) and later are rolled into various shapes, such as round rods and bars, using shaped rolls. Hot-rolled round rods (wire rod) are used as the starting material for rod- and wire-drawing operations (Chapter 15).

In the hot rolling of blooms, billets, and slabs, the surface of the material usually is **conditioned** (prepared for a subsequent operation) prior to rolling them. Conditioning is done by means such as using a torch (*scarfing*) to remove heavy scale or by rough grinding to smoothen surfaces. Prior to cold rolling, the scale developed during hot rolling may be removed by *pickling* with acids (acid etching), by such mechanical means as blasting with water, or by grinding to remove other defects as well.

Cold rolling is carried out at room temperature and, compared with hot rolling, produces sheets and strips with a much better surface finish (because of lack of scale), dimensional tolerances, and mechanical properties (because of strain hardening).

Pack rolling is a flat-rolling operation in which two or more layers of metal are rolled together, thus improving productivity. *Aluminum foil*, for example, is pack rolled in two layers, so only the top and bottom outer layers have been in contact with the rolls. Note that, one side of aluminum foil is matte, while the other side is shiny. The foil-to-foil side has a matte and satiny finish, but the foil-to-roll side is shiny and bright because it has been in contact under high contact stresses with the polished rolls during rolling.

Rolled mild steel, when subsequently stretched during sheet-forming operations, undergoes *yield-point elongation* (Section 16.3)—a phenomenon that causes surface irregularities called *stretcher strains* or *Lüder's bands*. To correct this situation, the sheet metal is subjected to a final, light pass of 0.5 to 1.5% reduction known as **temper rolling** or **skin pass**.

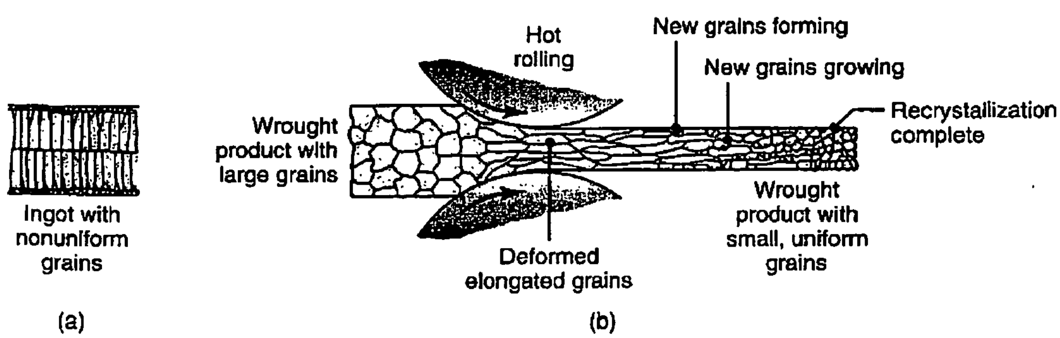

FIGURE 13.6 Changes in the grain structure of cast or of large-grain wrought metals during hot rolling. Hot rolling is an effective way to reduce grain size in metals for improved strength and ductility. Cast structures of ingots or continuous castings are converted to a wrought structure by hot working.

shearing and slitting operations (Section 16.2). Alligatoring (Fig. 13.8d) is a complex phenomenon and typically is caused by nonuniform bulk deformation of the billet during rolling or by the presence of defects in the original cast material.

13.3.2 Other characteristics of rolled metals

Residual stresses. Because of nonuniform deformation of the material in the roll gap, residual stresses can develop in rolled plates and sheets, especially during cold rolling. Small-diameter rolls or small thickness reductions-per-pass tend to deform the metal plastically more at its surfaces than in the bulk (Fig. 13.9a). This situation results in compressive residual stresses on the surfaces and tensile stresses in the bulk. Conversely, large-diameter rolls or high reductions-per-pass tend to deform the bulk more than the surfaces (Fig. 13.9b). This is due to the higher frictional constraint at the surfaces along the arc of contact—a situation that produces residual stress distributions that are the opposite of those in the case of small-diameter rolls.

Dimensional tolerances. Thickness tolerances for cold-rolled sheets usually range from ±0.1 to 0.35 mm (±0.004 to 0.014 in.), depending on the thickness. Tolerances are much greater for hot-rolled plates because of thermal effects. *Flatness tolerances* are usually within ±15 mm/m (±3/16 in./ft) for cold rolling and ±55 mm/m (5/8 in./ft) for hot rolling.

Surface roughness. The ranges of surface roughness in cold and hot rolling are given in Fig. 23.13 which, for comparison, includes ranges for other manufacturing processes. Note that cold rolling can produce a very fine surface finish, hence products made of cold-rolled sheets may not require additional finishing operations, depending on the application. Note also that hot rolling and sand casting produce the same range of surface roughness.

Gage numbers. The thickness of a sheet usually is identified by a *gage number:* the smaller the number, the thicker the sheet. Several numbering systems are used in

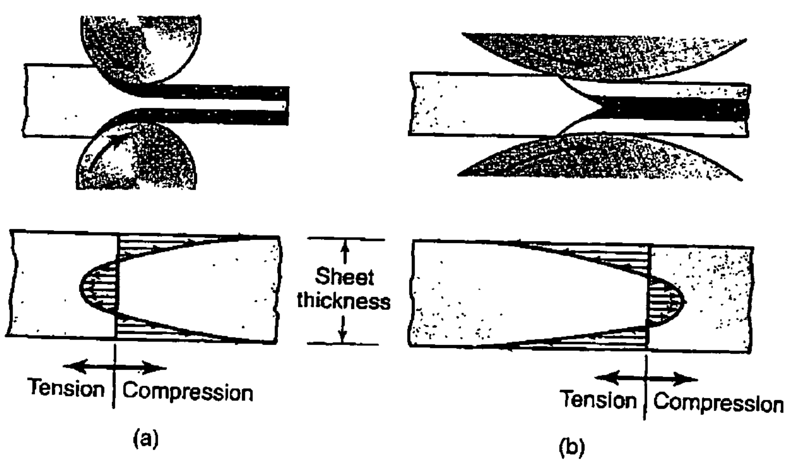

FIGURE 13.9 (a) Residual stresses developed in rolling with small-diameter rolls or at small reductions in thickness per pass. (b) Residual stresses developed in rolling with large-diameter rolls or at high reductions-per-pass. Note the reversal of the residual stress patterns.

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TABLE 16.2

Characteristics of Metals Important in Sheet-Forming Operations

Characteristic	Importance
Elongation	Determines the capability of the sheet metal to stretch without necking and failure; high strain-hardening exponent (*n*) and strain-rate sensitivity exponent (*m*) are desirable
Yield-point elongation	Typically observed with mild-steel sheets (also called Lüder's bands or stretcher strains), flamelike depressions on the sheet surface, can be eliminated by temper rolling but sheet must be formed within a certain time after rolling
Anisotropy (planar)	Exhibits different behavior in different planar directions, present in cold-rolled sheets because of preferred orientation or mechanical fibering, causes earing in deep drawing, can be reduced or eliminated by annealing but at lowered strength
Anisotropy (normal)	Determines thinning behavior of sheet metals during stretching, important in deep drawing
Grain size	Determines surface roughness on stretched sheet metal, the coarser the grain—the rougher the appearance (orange peel), also affects material strength.
Residual stresses	Typically caused by nonuniform deformation during forming, results in part distortion when sectioned, can lead to stress-corrosion cracking, reduced or eliminated by stress relieving.
Springback	Due to elastic recovery of the plastically deformed sheet after unloading, causes distortion of part and loss of dimensional accuracy, can be controlled by techniques such as overbending and bottoming of the punch
Wrinkling	Caused by compressive stresses in the plane of the sheet, can be objectionable, depending on its extent, can be useful in imparting stiffness to parts by increasing their section modulus, can be controlled by proper tool and die design
Quality of sheared edges	Depends on process used; edges can be rough, not square, and contain cracks, residual stresses, and a work-hardened layer, which are all detrimental to the formability of the sheet; edge quality can be improved by fine blanking, reducing the clearance, shaving, and improvements in tool and die design and lubrication
Surface condition of sheet	Depends on sheet rolling practice; important in sheet forming as it can cause tearing and poor surface quality

uniform elongation and necking, the total elongation of the specimen (in terms of that for a 50-mm gage length) is also a significant factor in the formability of sheet metals.

Yield-point elongation. Low-carbon steels and some aluminum-magnesium alloys exhibit a behavior called *yield-point elongation*—having both upper and lower yield points (Fig. 16.12a). This behavior results in Lüder's bands (also called *stretcher-strain marks* or *worms*) on the sheet (Fig. 16.12b). These are elongated depressions on the surface of the sheet, such as can be found on the bottom of cans containing common household products (Fig. 16.12c). These marks may be objectionable in the final product, because coarseness in the surface degrades appearance and may cause difficulties in subsequent coating and painting operations.

The usual method of avoiding these marks is to eliminate or reduce yield-point elongation by reducing the thickness of the sheet 0.5 to 1.5% by cold rolling (temper or skin rolling). Because of strain aging, however, the yield-point elongation reappears after a few days at room temperature or after a few hours at higher temperatures. To prevent this undesirable occurrence, the material should be formed within a certain time limit (which depends on the type of the steel).

Anisotropy. An important factor that influences sheet-metal forming is *anisotropy* (*directionality*) of the sheet. Recall that anisotropy is acquired during the thermomechanical processing of the sheet, and that there are two types of anisotropy *crystallographic anisotropy* (preferred orientation of the grains) and *mechanical fibering* (alignment of impurities, inclusions, and voids throughout the thickness of the sheet). The relevance of this subject is discussed further in Section 16.4.

Grain size. As described in Section 1.4, grain size affects mechanical properties and influences the surface appearance of the formed part (*orange peel*). The smaller

30.9 | The Weld Joint, Quality, and Testing

Three distinct zones can be identified in a typical weld joint, as shown in Fig. 30.

1. *Base metal*
2. *Heat-affected zone*
3. *Weld metal*

The metallurgy and properties of the second and third zones strongly dep on the type of metals joined, the particular joining process, the filler metals use any), and welding process variables. A joint produced without a filler metal is ca *autogenous*, and its weld zone is composed of the *resolidified base metal*. A j made with a filler metal has a central zone called the *weld metal* and is compose a mixture of the base and the filler metals.

Solidification of the weld metal. After the application of heat and the ir duction of the filler metal (if any) into the weld zone, the weld joint is allowe cool to ambient temperature. The *solidification* process is similar to that in ca and begins with the formation of columnar (dendritic) grains. (See Fig. 10.3.) T grains are relatively long and form parallel to the heat flow. Because metals much better heat conductors than the surrounding air, the grains lie parallel t plane of the two components being welded (Fig. 30.18a). In contrast, the grains shallow weld are shown in Fig. 30.18b and c.

Grain structure and grain size depend on the specific metal alloy, the parti welding process employed, and the type of filler metal. Because it began in a m state, the weld metal basically has a *cast* structure, and since it has cooled slov has coarse grains. Consequently, this structure generally has low strength, tough and ductility. However, the proper selection of filler–metal composition or of treatments following welding can improve the mechanical properties of the join

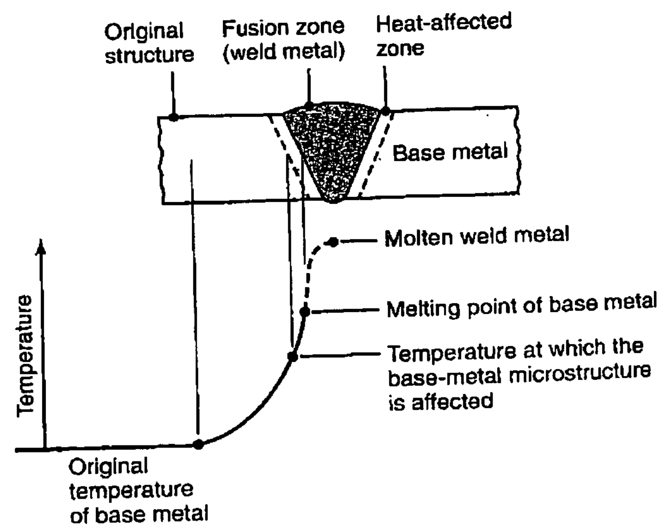

FIGURE 30.17 Characteristics of a typical fusion-weld zone in oxyfuel-gas and arc welding.

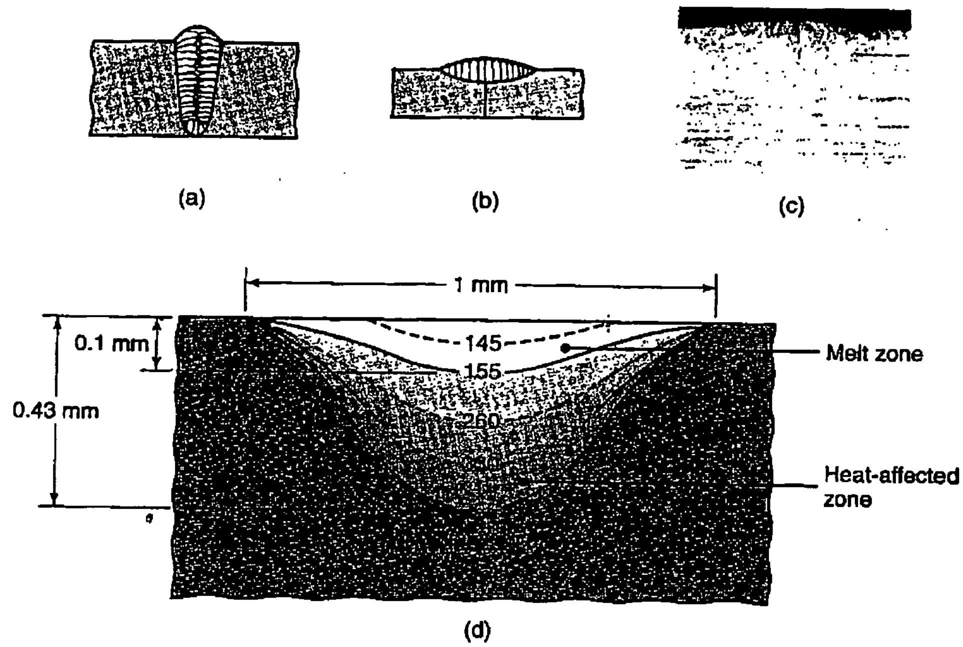

FIGURE 30.18 Grain structure in a (a) deep weld and (b) shallow weld. Note that the grains in the solidified weld metal are perpendicular to their interface with the base metal. (c) Weld bead on a cold-rolled nickel strip produced by a laser beam. (d) Microhardness (HV) profile across a weld bead.

The resulting structure depends on the particular alloy, its composition, and the thermal cycling to which the joint is subjected. For example, cooling rates may be controlled and reduced by *preheating* the general weld area prior to welding. Preheating is important particularly for metals having high thermal conductivity, such as aluminum and copper. Without preheating, the heat produced during welding dissipates rapidly through the rest of the parts being joined.

Heat-affected zone. The *heat-affected zone* (HAZ) is within the base metal itself. It has a microstructure different from that of the base metal prior to welding, because it has been subjected temporarily to elevated temperatures during welding. The portions of the base metal that are far enough away from the heat source do not undergo any structural changes during welding because of the far lower temperature to which they are subjected.

The properties and microstructure of the HAZ depend on (a) the rate of heat input and cooling and (b) the temperature to which this zone was raised. In addition to metallurgical factors (such as original grain size, grain orientation, and degree of prior cold work), physical properties (such as the specific heat and thermal conductivity of the metals) also influence the size and characteristics of this zone.

The strength and hardness of the heat-affected zone (Fig. 30.18d) depend partly on how the original strength and hardness of the base metal was developed prior to the welding. As was described in Chapters 2 and 4, they may have been developed by (a) cold working, (b) solid-solution strengthening, (c) precipitation hardening, or (d) various heat treatments. The effects of these strengthening methods are complex, and the

simplest to analyze are those in the base metal that has been cold-worked, such as b cold rolling or cold forging.

The heat applied during welding *recrystallizes* the elongated grains of the cold worked base metal. Grains that are away from the weld metal will recrystallize int fine, equiaxed grains. On the other hand, grains close to the weld metal have bee subjected to elevated temperatures for a longer period of time. Consequently, th grains will grow in size (grain growth), and this region will be softer and have lowe strength. Such a joint will be weakest at its heat-affected zone.

The effects of heat on the HAZ for joints made from dissimilar metals an for alloys strengthened by other methods are so complex as to be beyond th scope of this book. Details can be found in the more advanced references liste in the Bibliography at the end of this chapter. As a result of a history of therm cycling and its attendant microstructural changes, a welded joint may develo various discontinuities. Welding discontinuities can be caused also by inad quate or careless application of proper welding technologies or by poor operato training. The major discontinuities that affect weld quality are described in th next section.

30.9.1 Weld quality

As a result of a history of thermal cycling and its attendant microstructural change a welded joint may develop various discontinuities. Welding discontinuities also ca be caused by an inadequate or careless application of proper welding technologi or by poor operator training. The major discontinuities that affect weld quality a described here.

Porosity. *Porosity* in welds is caused by

- Gases released during melting of the weld area but trapped during solidificatio
- Chemical reactions during welding.
- Contaminants.

Most welded joints contain some porosity, which is generally in the shape of spheres or of elongated pockets. (See also Section 10.6.1.) The distribution of poro ity in the weld zone may be random, or the porosity may be concentrated in a ce tain region in the zone.

Porosity in welds can be reduced by the following practices:

- Proper selection of electrodes and filler metals.
- Improved welding techniques, such as preheating the weld area or increasin the rate of heat input.
- Proper cleaning and the prevention of contaminants from entering the weld zon
- Reduced welding speeds to allow time for gas to escape.

Slag inclusions. *Slag inclusions* are compounds such as oxides, fluxes, and ele trode-coating materials that are trapped in the weld zone. If shielding gases are no effective during welding, contamination from the environment also may contribute such inclusions. Welding conditions also are important; with control of welding proce parameters, the molten slag will float to the surface of the molten weld metal and th will not become entrapped.

Slag inclusions can be prevented by the following practices:

- Cleaning the weld-bead surface before the next layer is deposited by means of a wire brush (hand or power) or chipper.
- Providing sufficient shielding gas.
- Redesigning the joint to permit sufficient space for proper manipulation of the puddle of molten weld metal.

Incomplete fusion and penetration. *Incomplete fusion* (lack of fusion) produces poor weld beads, such as those shown in Fig. 30.19. A better weld can be obtained by the use of the following practices:

- Raising the temperature of the base metal.
- Cleaning the weld area before welding.
- Modifying the joint design and changing the type of electrode used.
- Providing sufficient shielding gas.

Incomplete penetration occurs when the depth of the welded joint is insufficient. Penetration can be improved by the following practices:

- Increasing the heat input.
- Reducing the travel speed during the welding.
- Modifying the joint design.
- Ensuring that the surfaces to be joined fit each other properly.

Weld profile. *Weld profile* is important not only because of its effects on the strength and appearance of the weld, but also because it can indicate incomplete fusion or the presence of slag inclusions in multiple-layer welds.

- Underfilling results when the joint is not filled with the proper amount of weld metal (Fig. 30.20a).
- Undercutting results from the melting away of the base metal and the consequent generation of a groove in the shape of a sharp recess or notch (Fig. 30.20b). If it

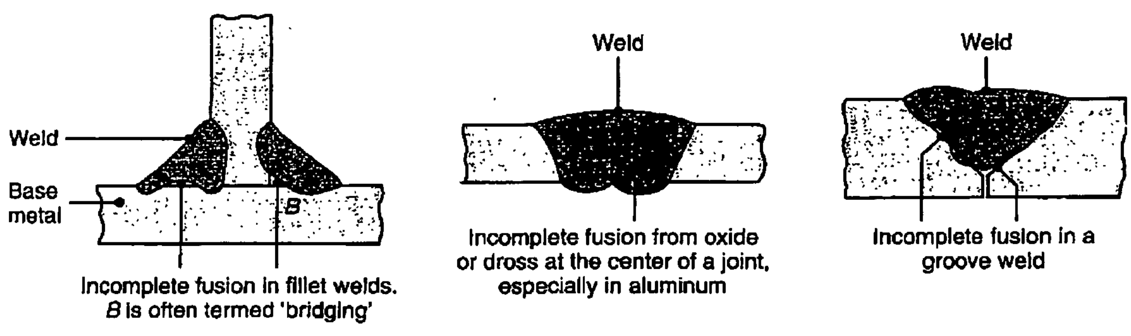

FIGURE 30.19 Examples of various discontinuities in fusion welds.

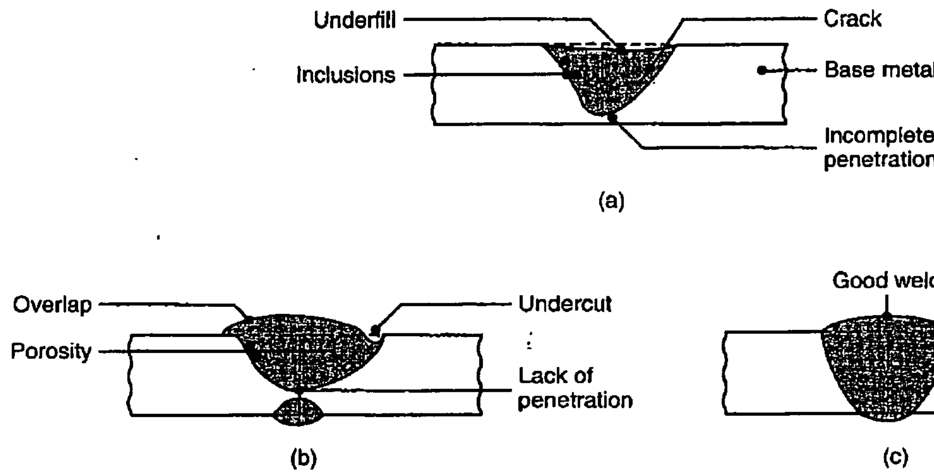

FIGURE 30.20 Examples of various defects in fusion welds.

is deep or sharp, an undercut can act as a stress raiser and can reduce the fatigue strength of the joint; in such cases, it may lead to premature failure.

- Overlap is a surface discontinuity (Fig. 30.20b) usually caused by poor welding practice or by the selection of improper materials. A good weld is shown in Fig. 30.20c.

Cracks. Cracks may occur in various locations and directions in the weld area. Typical types of cracks are longitudinal, transverse, crater, underbead, and toe cracks (Fig. 30.21).

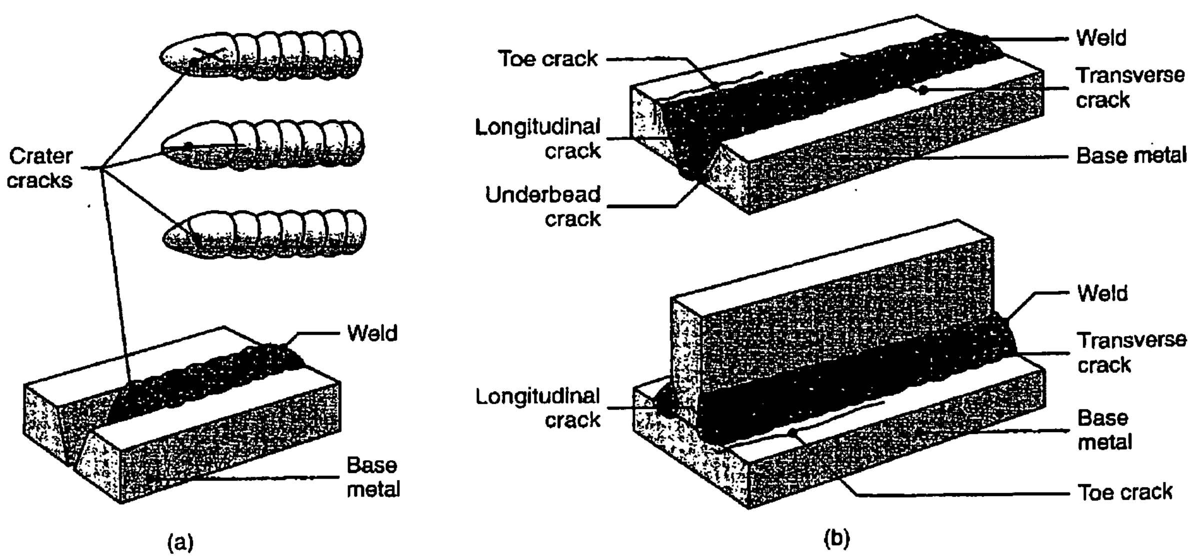

FIGURE 30.21 Types of cracks developed in welded joints. The cracks are caused by thermal stresses, similar to the development of hot tears in castings, as shown in Fig. 10.12.

FIGURE 30.22 Crack in a weld bead. The two welded components were not allowed to contract freely after the weld was completed. *Source:* Courtesy of Packer Engineering.

These cracks generally result from a combination of the following factors:

- Temperature gradients that cause thermal stresses in the weld zone.
- Variations in the composition of the weld zone that cause different rates of contraction during cooling.
- Embrittlement of grain boundaries (Section 1.4), caused by the segregation of such elements as sulfur to the grain boundaries, and when the solid–liquid boundary moves when the weld metal begins to solidify.
- Hydrogen embrittlement (Section 2.10.2).
- Inability of the weld metal to contract during cooling (Fig. 30.22). This is a situation similar to *hot tears* that develop in castings (Fig 10.12) and is related to excessive restraint of the workpiece during the welding operation.

Cracks also are classified as **hot cracks** that occur while the joint is still at elevated temperatures and **cold cracks** that develop after the weld metal has solidified. The basic crack-prevention measures in welding are the following:

- Modify the joint design to minimize stresses developed from shrinkage during cooling.
- Change the parameters, procedures, and sequence of the welding operation.
- Preheat the components to be welded.
- Avoid rapid cooling of the welded components.

Lamellar tears. In describing the anisotropy of plastically deformed metals in Section 1.5, it was stated that the workpiece is weaker when tested in its thickness direction because of the alignment of nonmetallic impurities and inclusions (stringers). This condition is evident particularly in rolled plates and in structural shapes. In welding

such components, *lamellar tears* may develop because of shrinkage of the restrained components of the structure during cooling. Such tears can be avoided by providing for shrinkage of the members or by modifying the joint design to make the weld bead penetrate the weaker component more deeply.

Surface damage. Some of the metal may spatter during welding and be deposited as small droplets on adjacent surfaces. In arc-welding processes, the electrode inadvertently may touch the parts being welded at places other than the weld zone (arc strikes). Such surface discontinuities may be objectionable for reasons of appearance or of subsequent use of the welded part. If severe, these discontinuities adversely may affect the properties of the welded structure, particularly for notch-sensitive metals. Using proper welding techniques and procedures is important in avoiding surface damage.

Residual stresses. Because of localized heating and cooling during welding, the expansion and contraction of the weld area causes *residual stresses* in the workpiece. (See also Section 2.11.) Residual stresses can lead to the following defects:

- Distortion, warping, and buckling of the welded parts (Fig. 30.23).
- Stress-corrosion cracking (Section 2.10.2).
- Further distortion, if a portion of the welded structure is subsequently removed, such as by machining or sawing.
- Reduced fatigue life of the welded structure.

The type and distribution of residual stresses in welds is described best by reference to Fig. 30.24a. When two plates are being welded, a long, narrow zone is subjected to elevated temperatures, while the plates, as a whole, are essentially at ambient temperature. After the weld is completed and as time elapses, the heat from the weld zone dissipates laterally into the plates, while the weld area cools. Thus, the plates begin to expand longitudinally, while the welded length begins to contract (Fig. 30.22a).

If the plate is not constrained, it will warp, as shown in Fig. 30.22a. However, if the plate is not free to warp, it will develop residual stresses that typically are distributed like those shown in Fig. 30.24. Note that the magnitude of the compressive residual stresses in the plates diminishes to zero at a point far

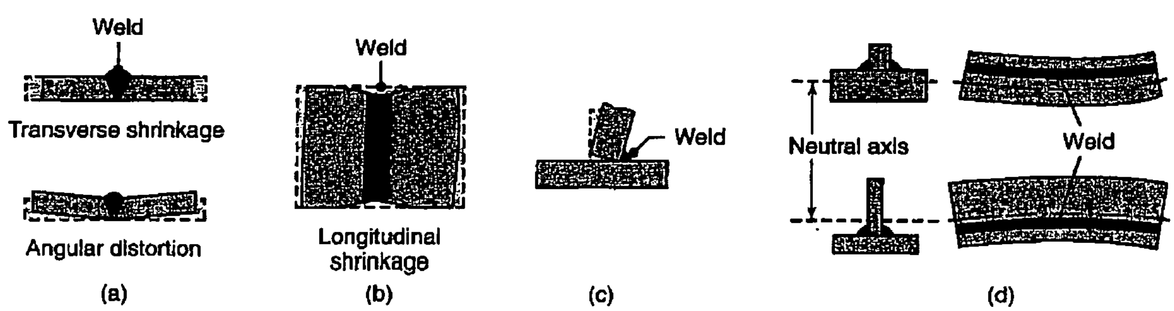

FIGURE 30.23 Distortion of parts after welding. Distortion is caused by differential thermal expansion and contraction of different regions of the welded assembly.

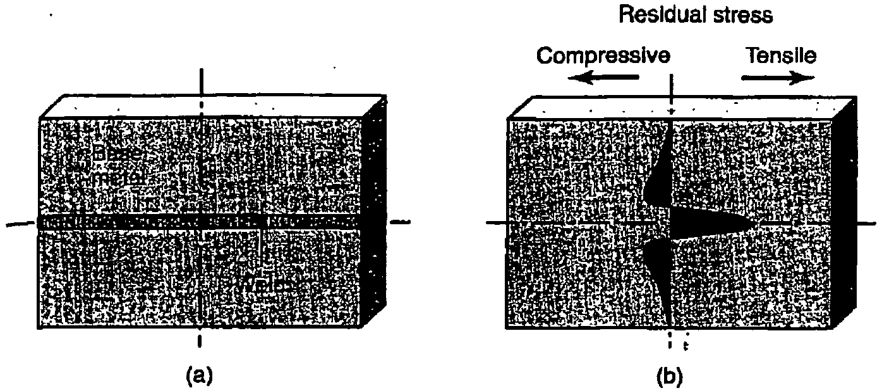

FIGURE 30.24 Residual stresses developed in (a) a straight-butt joint. Note that the residual stresses shown in (b) must be balanced internally. (See also Fig. 2.29.)

away from the weld area. Because no external forces are acting on the welded plates, the tensile and compressive forces represented by these residual stresses must balance each other.

Events leading to the distortion of a welded structure is shown in Fig. 30.25. Before welding, the structure is stress-free, as shown in Fig. 30.25a. The shape may be fairly rigid, and fixturing also may be present to support the structure. When the weld bead is placed, the molten metal fills the gap between the surfaces to be joined, and flows outward to form the weld bead. At this point, the weld is not under any stress. Afterward, the weld bead solidifies, and both the weld bead and the surrounding material cool to room temperature. As these materials cool, they try to contract but are constrained by the bulk of the weldment. The result is that the weldment distorts (Fig. 30.25c) and residual stresses develop.

The residual-stress distribution shown places the weld and the HAZ in a state of residual tension, which is harmful from a fatigue standpoint. Many welded structures will use cold-worked materials (such as extruded or roll-formed shapes), and these are relatively strong and fatigue-resistant. The weld itself may have porosity (see Fig. 30.20b), which can act as a stress riser and aid fatigue-crack growth, or there could be other cracks that can grow in fatigue. In general, the HAZ is less fatigue-resistant than

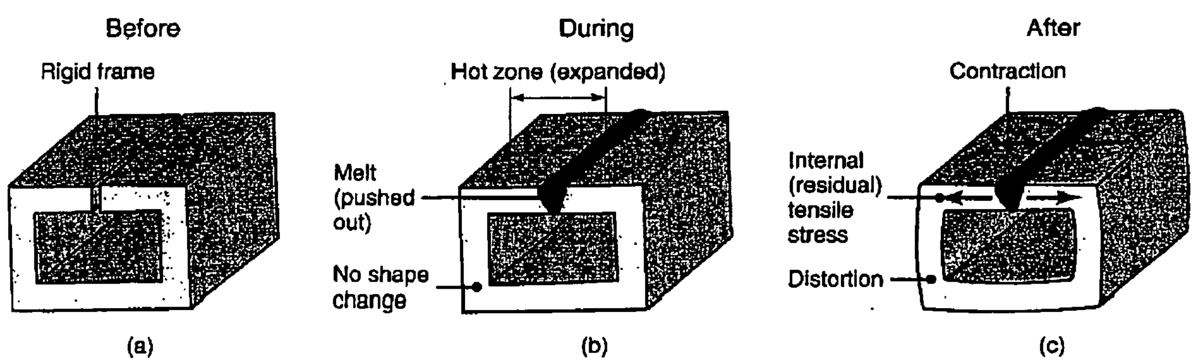

FIGURE 30.25 Distortion of a welded structure. *Source*: After J.A. Schey.

the base metal. Thus, the residual stresses developed can be very harmful, and it is not unusual to further treat welds in highly stressed or fatigue-susceptible applications, as discussed next.

In complex welded structures, residual-stress distributions are three-dimensional and, consequently, difficult to analyze. The previous discussion involved two plates that were not restrained from movement. In other words, the plates were not an integral part of a larger structure. On the other hand, if they are restrained, reaction stresses will be generated, because the plates are not free to expand or contract. This situation arises particularly in structures with high stiffness.

Stress relieving of welds. The problems caused by residual stresses (such as distortion, buckling, and cracking) can be reduced by preheating the base metal or the parts to be welded. Preheating reduces distortion by reducing the cooling rate and the level of thermal stresses developed (by lowering the elastic modulus). This technique also reduces shrinkage and possible cracking of the joint.

For optimum results, preheating temperatures and cooling rates must be controlled carefully in order to maintain acceptable strength and toughness in the welded structure. The workpieces may be heated in several ways, including: (a) in a furnace, (b) electrically (resistively or inductively), or (c) by radiant lamps or a hot-air blast for thin sections. The temperature and time required for *stress relieving* depend on the type of material and on the magnitude of the residual stresses developed.

Other methods of stress relieving include peening, hammering, or surface rolling of the weld-bead area. These techniques induce compressive residual stresses, which, in turn, lower or eliminate tensile residual stresses in the weld. For multilayer welds, the first and last layers should not be peened in order to protect them against possible peening damage.

Residual stresses also can be relieved or reduced by plastically deforming the structure by a small amount. For instance, this technique can be used in welded pressure vessels by pressurizing the vessels internally (*proof-stressing*). In order to reduce the possibility of sudden fracture under high internal pressure, the weld must be made properly and must be free of notches and discontinuities, which could act as points of stress concentration.

In addition to being preheated for stress relieving, welds may be *heat treated* by various other techniques in order to modify other properties. These techniques include the annealing, normalizing, quenching, and tempering of steels and the solution treatment and aging of various alloys as described in Chapter 4.

30.9.2 Weldability

The *weldability* of a metal usually is defined as its capacity to be welded into a specific structure that has certain properties and characteristics and will satisfactorily meet service requirements. Weldability involves a large number of variables, hence generalizations are difficult. As noted previously, the material characteristics (such as alloying elements, impurities, inclusions, grain structure, and processing history) of both the base metal and the filler metal are important. For example, the weldability of steels decreases with increasing carbon content because of martensite formation (which is hard and brittle) and thus reduces the strength of the weld. Coated steel sheets present various challenges in welding, depending on the type and thickness of the coating.

Because of the effects of melting and solidification and of the consequent microstructural changes, a thorough knowledge of the phase diagram and the response

of the metal or alloy to sustained elevated temperatures is essential. Also influencing weldability are mechanical and physical properties: strength, toughness, ductility, notch sensitivity, elastic modulus, specific heat, melting point, thermal expansion, surface-tension characteristics of the molten metal, and corrosion resistance.

Preparation of surfaces for welding is important, as are the nature and properties of surface-oxide films and of adsorbed gases. The particular welding process employed significantly affects the temperatures developed and their distribution in the weld zone. Other factors that affect weldability are shielding gases, fluxes, moisture content of the coatings on electrodes, welding speed, welding position, cooling rate, and level of preheating, as well as such post-welding techniques as stress relieving and heat treating.

Weldability of ferrous materials:

- *Plain-carbon steels:* Weldability is excellent for low-carbon steels, fair to good for medium-carbon steels, poor for high-carbon steels.
- *Low-alloy steels:* Weldability is similar to that of medium-carbon steels.
- *High-alloy steels:* Weldability generally is good under well-controlled conditions.
- *Stainless steels:* These generally are weldable by various processes.
- *Cast irons:* These generally are weldable, although their weldability varies greatly.

Weldability of nonferrous materials:

- *Aluminum alloys:* These are weldable at a high rate of heat input. An inert shielding gas and lack of moisture are important. Aluminum alloys containing zinc or copper generally are considered unweldable.
- *Copper alloys:* Depending on composition, these generally are weldable at a high rate of heat input. An inert shielding gas and lack of moisture are important.
- *Magnesium alloys:* These are weldable with the use of a protective shielding gas and fluxes.
- *Nickel alloys:* Weldability is similar to that of stainless steels. Lack of sulfur is important.
- *Titanium alloys:* These are weldable with the proper use of shielding gases.
- *Tantalum:* Weldability is similar to that of titanium.
- *Tungsten:* Weldable under well-controlled conditions.
- *Molybdenum:* Weldability is similar to that of tungsten.
- *Niobium (Columbium):* Weldability is good.

30.9.3 Testing of welds

As in all manufacturing processes, the quality of a welded joint is established by testing. Several standardized tests and test procedures have been established. They are available from many organizations, such as the American Society for Testing and Materials (ASTM), the American Welding Society (AWS), the American Society of Mechanical Engineers (ASME), the American Society of Civil Engineers (ASCE), and various federal agencies.